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RECENT WORK ON MEASUREMENT OF UNDERWATER EXPLOSION PRESSURES

7 AUGUST 1968

NOL

UNITED STATES NAVAL ORDNANCE LABORATORY, WHITE OAK, MARYLAND

NOLTR 68-78

47

RECENT WORK ON MEASUREMENT OF UNDERWATER EXPLOSION PRESSURES

by

E. Swift, Jr.
John P. Slifko

ABSTRACT: British and United States data obtained in the 1950's on underwater explosion shock wave pressures of TNT differed, the U. S. being 25% higher. Half of this discrepancy was shown to be caused by differences in recording and calibrating techniques. Recent work at NOL has indicated that the gage is the major cause of current discrepancies. Comparisons of NOL and NCRE gage outputs were made both at NCRE and at NOL; a 10-16% greater pressure was given by the NCRE gages.

The scatter in pressure measurements with NOL gages is shown to be the same now as in the 1950's; namely, 90% of the data falls within ± 12 and 14% of the best line through the data for two standard explosives. An improved method of waterproofing the gage with oil resulted in 90% of the measurements falling within ±8% of the best line in preliminary tests.

Further exchange of information and agreement on common standards is recommended.

PUBLISHED 7 AUGUST 1968

UNDERWATER EXPLOSIONS DIVISION
EXPLOSIONS RESEARCH DEPARTMENT
U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, SILVER SPRING, MARYLAND

NOLTR 68-78 7 August 1968

RECENT WORK ON MEASUREMENT OF UNDERWATER EXPLOSION PRESSURES

This report is based on a paper prepared for the IEP ABC-25 Conference on "Operational Implications and Limitations of NBC Defense", held in London May 13-17, 1968. It is being issued as a technical report to give wider distribution.

The work reported here has been carried out over two decades under a variety of tasks; writing of this report was done under Naval Ordnance Systems Command Task ORD-033-211/092-1/F008-08-11.

Mention of commercially available materials does not constitute an endorsement or criticism by the Laboratory.

E. F. SCHREITER
Captain, USN
Commander

C J Aronson

C. J. ARONSON
By direction

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RECENT WORK ON MEASUREMENT OF UNDERWATER EXPLOSION PRESSURES

1. INTRODUCTION

Over the past 25 years, both the British and United States laboratories have been engaged in the business of measuring underwater explosion pressures for weapon development purposes. We have faced common problems leading to uncertainties in the results and have worked over the years to find the causes of these uncertainties and to reduce or eliminate them.

In both countries we have recognized the limitations of our experiments. In such field work one does not have laboratory-type controlled conditions with high accuracies, but is subject to changes in experimental conditions which cannot always be recognized or accounted for. Therefore, we have had to design our experiments to accommodate to the practical necessities and still obtain acceptable and useful results.

This has meant always making a number of measurements--sometimes a large number, with a statistical evaluation of the results. It has meant randomization of charges or equipment in any set of experiments; and, of course, it has meant great care in setting up experiments, calibrating, and making measurements to do so in as reproducible a manner as possible.

The uncertainties in our results were based not only on the lack of precision in the measurements, but also on the poor agreement with the British values for TNT obtained about 1950-51 (references 1-4).* Absolute values for TNT were highly desirable at that time since nuclear explosion yields were given in "kilotons of TNT" and TNT was the common standard high explosive. The difference between the Naval Construction Research Establishment (NCRE) and Naval Ordnance Laboratory (NOL) TNT shock wave peak pressures reported in 1959 (reference 4) was about 25%, the NOL values being higher. After a study and analysis of the two laboratories' recording systems was made in 1956-57, about 1/2 of the 25% difference could be accounted for and was taken care of subsequently by improvements in the gage calibration system and a redesign of amplifying circuits in the recording system.

N.C.R.E. has recently carried out some explosive comparison tests using Plastic Explosive (P.E.) as a standard. They report (reference 15) that the value of peak pressure for P.E. is 25-30% higher than Bebb's 1948 value (reference 2). This should bring the N.C.R.E. and NOL values of pressures into close agreement; however, comparative tests of gages reported in Section 4 show N.C.R.E. to be 10-16% higher than NOL.

This paper is intended to review the situation and to discuss some of the work recently done at NOL in an attempt to minimize the uncertainties and differences.

2. NOL MEASUREMENTS OF SHOCK WAVE PRESSURES

During the past two decades, NOL has made a large number of underwater shock wave pressure measurements. In most experiments designed to determine the relative effectiveness of new explosives, one or more "standard" explosives was usually fired.

*References are listed on Page 8.

Thus, an analysis of the accumulated standard explosive data may be useful in determining whether or not changes occurred in the level of measurement of the effectiveness of the standard explosive and whether or not an improvement has been made in the precision of the measurements in the last two decades. It should be noted that improvements and modifications have been made in most areas of the calibrating and recording instrumentation and in analytical methods in this period.

The standard explosives discussed here are HBX-1 and 50-50 pentolite. For comparison, old data obtained by the Woods Hole Oceanographic Institution (WHOI) in 1945-46 from 50- and 80-lb spherical HBX-1 charges (reference 3) and NOL in 1952-56 from 1.1-, 10-, 30-, and 50-lb HBX-1 charges (reference 5)were combined. The line shown in Figure 1 is that from reference 5. Some 90% of the peak shock wave pressures are within ± 12% of the line.

Old data for pentolite obtained at WHOI in 1945-47 using 1/2-, 1-, 50-, and 80-lb spheres (references 6, 7, 8) and at NOL in 1952 using approximately 1- and 44-lb charges (references 5, 9) were combined. The average line drawn in reference 5 is shown in Figure 2. Some 90% of the peak pressures fell within ± 14% of this line.

More recent NOL shock wave data for HBX-1 and pentolite are shown in Figures 1 and 2, respectively, as points representing individual peak pressure measurements. The data were obtained with wax-coated*, 4-ply** gages which were 1/4 in., 3/8 in. and 1/2 in. in diameter. The pressures were evaluated using the calibration constants obtained from bare gages in an oil-filled pressure chamber. The procedure used in determining peak pressures was that of extrapolating the pressure-time curve back to one-half the recorded rise time.

The HBX-1 data points shown in Figure 1 were obtained in 1963 from 10-, 32-, and 70-lb spherical charges (reference 10). Some 90% of the points were also within ± 12% of the line. The pentolite data points shown in Figure 2 were obtained from 1-lb spherical charges fired in 1965 (reference (11). Some 90% of the data points also fell within ± 14% of the reference 5 line.

It is apparent that the precision of the most recent pressure measurements did not show improvement, nor did the pressures depart significantly from the band of scatter of the older data. The most probable reason for this was that improvements were made in areas of instrumentation and analysis in which precision was already good and little if any improvement was made in the area which is the least precise and which we now identify as the gage.

3. WORK ON GAGES AT THE NAVAL ORDNANCE LABORATORY

We became greatly concerned with the problem of absolute values in connection with underwater pressure measurements on atomic weapons tests. Since each single datum is unique and expensive to obtain, great care was taken in the preparation of the recording system. In going through the preparatory process, we found that our greatest inconsistencies lay in the gages.

* Zophar Mills C-276 wax.

**i.e. four tourmaline discs, also referred to as 4-pile.

In these preparations, the static calibration values for uncoated gages were quite consistent--usually the scatter of each gage was within 1% of the norm--but when gages were placed side by side and subjected to the same underwater shock wave, the measured pressures differed widely. The spread of recorded pressures exceeded the 12% to 14% spreads obtained over several years from the standard explosives. This was a distressing situation, particularly since the preparation time was too short to conduct an investigation of the gage inconsistencies. Therefore, a practical approach to this problem was taken: we retained for atomic weapons tests only those gages that were within a band of ± 10% of the average pressure in dynamic tests.

Since that time we have scoured the market for other types of gage, but none has proven satisfactory. We have also carried out a variety of small scale experiments with tourmaline gages extending over several years. The gage materials, construction, calibration, mounting and, in particular, the gage coating, were examined in detail. Both static calibrations and underwater explosion tests were performed on a number of the above combinations. The details have not been published but are summarized in references 11 and 12. In essence, the results have indicated that the wax coating used on tourmaline gages appears to be the main factor contributing to the scatter of the shock wave pressures.

First, the wax coated gage produced a non-linear response when calibrated over a range of pressures. This effect could result in incorrect slopes of log-log curves of shock wave parameters plotted against $W^{1/3}/R$. Furthermore, the wax coated gage calibration constant* was larger than that of the bare gage, and there is some experimental evidence that the calibration constant increases as the wax thickness increases. Finally, these tests showed that the rise time of the shock wave recorded with wax coated gages increases as the pressure level decreases. This effect alone could result in erroneous pressures when the shock wave time constant is only several times the rise time, i.e., when recording from charges weighing a pound or less.

Consequently, a search was made for a more suitable coating material for the tourmaline gage. Materials tested were other wax, tar, epoxy, and rubber compounds. A sample of the wax** used by NCRE was included in the tests. These materials showed no significant improvement over the Zophar C-276 wax used by NOL for many years.

One promising lead is being investigated: the old idea of using an oil-filled capsule to waterproof the gage. A Tygon tube about 0.43 in. diam. and 0.06 in. thick was sealed at one end and then filled with 1000 cts. silicone oil. The gage terminals were soldered to two stiff leads which had been molded into a cylindrical epoxy oil barrier. The gage assembly was carefully inserted into the tube so that air bubbles would be eliminated and the tube was then clamped over the oil barrier. Finally, the cable was soldered to the leads at the other end of the barrier and this joint was waterproofed.

Preliminary results from this arrangement showed less scatter in shock wave pressure measurements than do wax coated gages. Also the recorded rise times

*Use of a larger gage calibration constant results in a lower calculated pressure.

**Insowax 430, kindly furnished by Campbell Technical Waxes, Ltd., Crayford, Kent.

(~ 5 microsec) approached theoretical values and were independent of the pressure levels recorded in these tests. The calibration results apparently were not affected by this coating since the gage response was linear with calibration pressure level and the calibration constant was essentially that of the bare gage. One current characteristic of this gage covering is that oscillations--severe at times--are usually recorded on the initial portion of the shock wave. In general, the periods of these oscillations were from 6 to 8 microsec and the oscillations disappeared in two or three cycles. This effect introduces no problems in recording most exponentially decaying pressure pulses since in all cases the extrapolation method is used in determining peak pressures; however, it might be troublesome in some cases, particularly in recording from small charges.

In reference 11, a comparison is made of the shock wave peak pressures recorded with standard 4-ply, 1/4 in. diam. gages covered with epoxy plastic, Zophar C-276 wax, and silicone oil. Twelve 1-lb spherical pentolite charges were fired and 4 to 5 gages of each type were used on each shot at the same distance. The results from the wax coated gages are the plotted points in Figure 2. In Table 1, those wax coated gage pressures are compared with the oil covered gage pressures measured at four distances. It can be seen that the two sets of data disagree; also the scatter is much less for the oil-covered gages at the two lower pressures. At the higher pressures, the scatter of the two sets of data is essentially the same. If all the data are considered, 90% of the data points obtained with the oil covered gages fall within ± 8% of the line shown in Figure 2. This figure is ± 14% for the wax coated gages, as discussed in Section 2.

Since both static and dynamic characteristics of the oil covered gage show improvement over the wax coated gage, further development and testing of this arrangement is indicated. Some possibilities for further work are given in Section 6.

4. RECENT GAGE COMPARISONS

Recently, it became more important to resolve the differences between U.S. and U.K. underwater measurements, since new explosives under development in both countries should be compared and because we are carrying out a combined program of explosion damage tests and examining damage mechanisms. The most suspect cause of discrepancies appeared to be the pressure pickup--the U.S. and the U.K. have developed and are using piezoelectric gages made from tourmaline discs.

In 1965, NCRE took the initiative by comparing directly three standard 1/4-in. diam. 2-ply NCRE gages with three standard 1/4-in. diam. 4-ply NOL gages in calibration and underwater shock wave tests (reference 13). The recording and calibration equipment and methods of data analysis used were identical for both cases. The NCRE calibration of the wax-coated NOL gages was only 1% to 5% less than the comparable NOL calibration; however, there was an average difference of about 13% in the shock wave peak pressures from the thirty-eight 3-oz. charges fired, and the values obtained with the NOL gages were now lower than the NCRE gage values.

In 1967, NOL reciprocated by performing a direct comparison on another set of 3 NCRE and 3 NOL gages in static and dynamic pressure tests. The NCRE static calibration of their gages at the 500 lbs/in^2 level was 3% to 8% less than the comparable NOL calibrations of the wax-coated NCRE gages, but the difference increased at lower pressure levels. Using identical recording equipment and methods of data analysis for the 2 sets of gages, the average shock wave pressure recorded by NOL from 4 shots with 3 NCRE gages was 655 lbs/in^2 as compared with 565 lbs/in^2 for 3 NOL gages on the same shots; the gage sensitivities provided by each Laboratory for wax coated gages were used (reference 14). This 16% difference was reduced to 10% when the NOL calibration of the NCRE gages was used in the pressure calculations. Thus, although the calibration and recording equipment, methods of data analysis, pressure levels, and shock wave forms were different on the two tests, the results of the 1967 NOL tests were in agreement with those of the 1965 NCRE tests--that the shock wave pressures provided by the NOL gages were on the average 10 to 16% lower than those from the NCRE gages.

In 1966, AWRE and NCRE (reference 15) conducted underwater shock wave tests in which each establishment used its own recording equipment and 4 to 5 gages on each shot. Both laboratories used essentially the same type of tourmaline gage; i.e., 1/4 in. diam., 2-ply, coated with Insowax 430; however, the NCRE gages used stiffer fasteners in the attachment of the crystal head to the cable. The laboratories agreed to within 2% in calibrating the wax coated gages provided by both laboratories each using its own calibration system. On measuring pressures from the shots, both laboratories obtained a ± 10% scatter in the peak pressures, but the mean lines gave different slopes. Agreement in pressure values was obtained at the close-in distances; however, the NCRE line was about 25% above the AWRE line at the extreme range ($W^{1/3}/D = 0.15$).

Thus the present status of underwater shock wave pressure measurements seems to be that no two laboratories are in sufficiently close agreement to provide confidence in the exact absolute values of shock wave parameters for any explosive.

5. SUMMARY

1. Peak pressure values obtained for TNT in the 1950's by NOL were some 25% higher than NCRE values. Subsequent improvements in recording and calibrating techniques should have decreased the difference to about 12%; however, no direct comparisons have been made.

2. In spite of improvements in techniques of recording, calibration, and analysis, recent NOL pressure measurements show the same scatter as in the 1950's: 90% of the measurements fall within ± 12% to ± 14% of the best line through the data. This scatter is attributed to the gage, which has not been changed in this period. It was suspected that any remaining differences between NOL and NCRE pressure values could also be traced to the gages used.

3. Comparisons of U.S. and British gages were carried out both at NCRE and at NOL. Charges were fired at NCRE and NOL gages placed side by side. A discrepancy was found; the NCRE gages gave 10% to 16% <u>higher</u> pressure readings, in contrast to the earlier results with TNT.

4. In an attempt to resolve this discrepancy and to improve the scatter of pressures found with NOL gages, a program of investigation of the NOL gage was undertaken. The effect on the recorded underwater pressure of changes in calibration, construction, mounting, and coating of gages was studied; the last appears to be a significant factor. Tests with a gage in an oil-filled capsule used for waterproofing gave more reproducible results on explosion tests than did the usual wax coating: 90% of the measured points fell within ± 8% of the best line through the data.

6. RECOMMENDATIONS FOR FUTURE WORK

It is believed that the precision* of underwater explosion pressure measurements can be improved by developing a better gage. Some recommendations are:

(a) Investigate various elastomeric silicone compounds for waterproofing gages.

(b) Continue experiments with the oil covered gages, in order to find the best arrangement of tubing, fluid, barrier, and cable connection to minimize scatter and noise.

(c) Investigate the effect of the gage diameter to thickness ratio and the effect of the method of mounting the gage on the cable.

(d) Eventually, it may be necessary to initiate a program of quality control in gage construction. The best quality tourmaline should be used and the gages should be constructed with great precision; i.e., the crystal faces, electrodes, and the connection tabs should be optically flat so that empty spaces, however minute, are eliminated in the assembly.

Better agreement between U.S. and U.K. laboratories should come about** as a result of interchanges of information and adoption of common standards. Thus, a "best" method of gage calibration should be sought, preferably an absolute dynamic calibration, so that we can determine the absolute accuracy of our measurements. Also, for comparison purposes, a mutually agreed-on standard explosive charge would allow direct comparison of a new explosive's output relative to a common standard.

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* How precise do pressure measurements need to be? Practically, the precision of the gage measurement need be only adequate to determine significant differences in the parameter under investigation. Thus, on atomic weapons tests, the yield might be known only to ± 10%. Since pressure is proportional to:

$$\left(\frac{W^{1/3}}{R}\right)^{1.13}$$

a 10% variation in the yield, W, can be shown to correspond to 3.8% in pressure. This precision may be reached by an improved gage, or by making a great enough number of measurements with current gages. Obviously, the better the gage, the fewer the measurements needed for any desired precision.

** A personal communication from D. J. James, AWRE, to E. Swift, Jr., NOL, transmitting preliminary data, indicates that better agreement than discussed here may have already been obtained.

TABLE I. COMPARISON OF SHOCK WAVE PEAK PRESSURES* FROM WAX AND OIL COATED GAGES. CHARGE: 1-lb PENTOLITE

Gage No.	R = 2 Ft.	R = 3.5 Ft.	R = 7 Ft.	R = 10 Ft.
		WAX COATED GAGE		
2321	12,000	5890	2630	1620
	11,500	6020	2630	1780
	10,950		2755	1820
2280	10,450	5820	2690	1820
	10,600	5370	2755	--
	10,700		2290	1150
2288	--	5750	2570	1660
	--	5690	2690	1780
	10,600		2240	1230
2320	10,950	5750	--	--
	10,450	5750	2660	1700
	10,850		2110	1200
AVE.	10,905	5755	2547	1576
	σ = 4.5%	σ = 3.3%	σ = 8.8%	σ = 17.3%
		OIL COATED GAGE		
2528	11,200	5370	2570	1700
	11,200	5620	2510	1620
	11,500		2630	1740
2529	11,750	5500	--	1780
	11,600	5620	2400	1620
	--		2690	--
2530	11,100	--	--	1680
	10,950	--	2430	1620
	11,500		--	1660
2494	12,700	--	2570	1660
	11,500	5750	--	--
	--	--	2455	1680
AVE.	11,500	5572	2532	1676
	σ = 4.3%	σ = 2.5%	σ = 4%	σ = 3.2%

* Pressures are in $lb/in.^2$
σ = standard deviation

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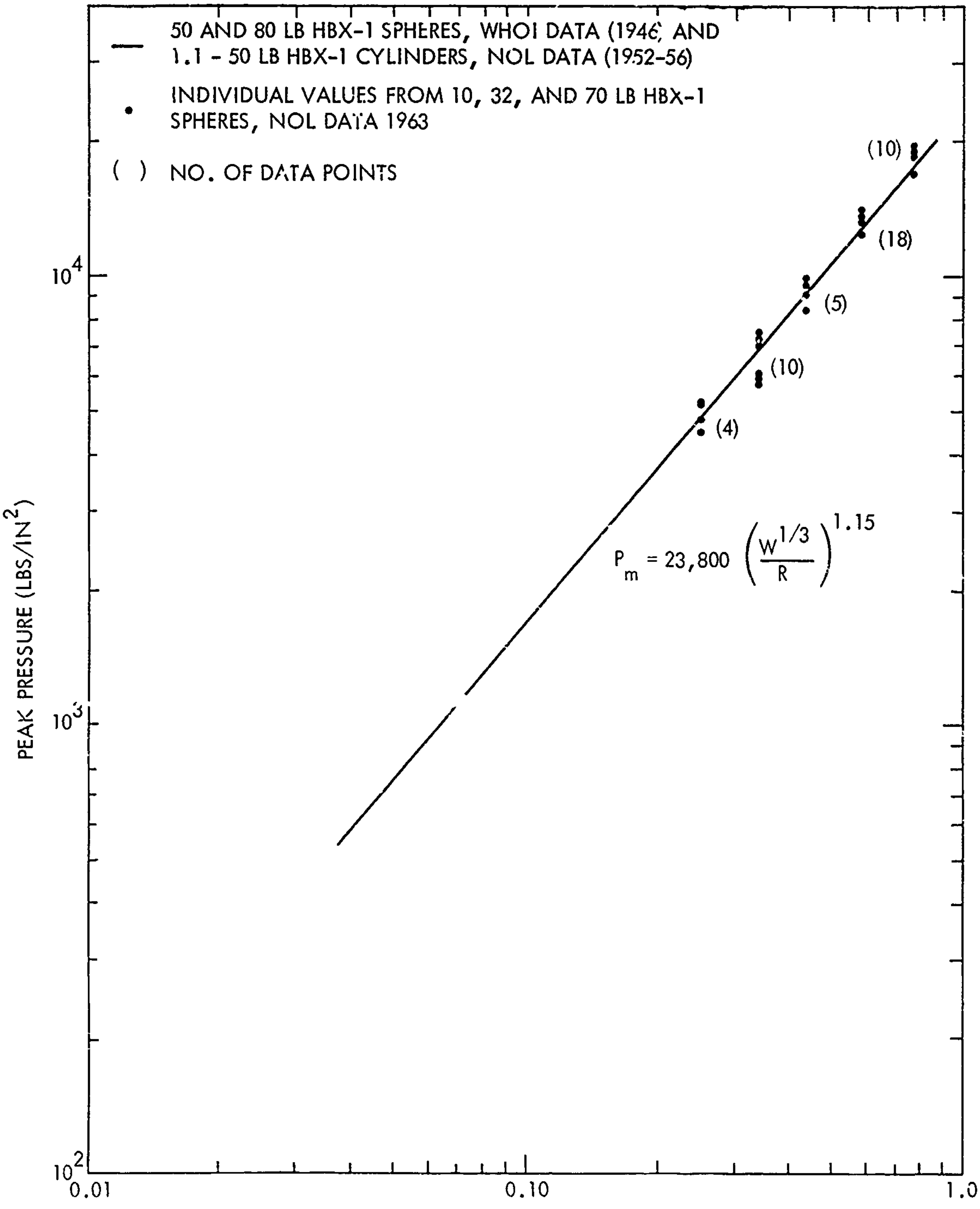

FIG.1 A COMPARISON OF RECENT WITH OLD U.S. MEASUREMENTS OF SHOCK WAVE PEAK PRESSURES FROM HBX-1

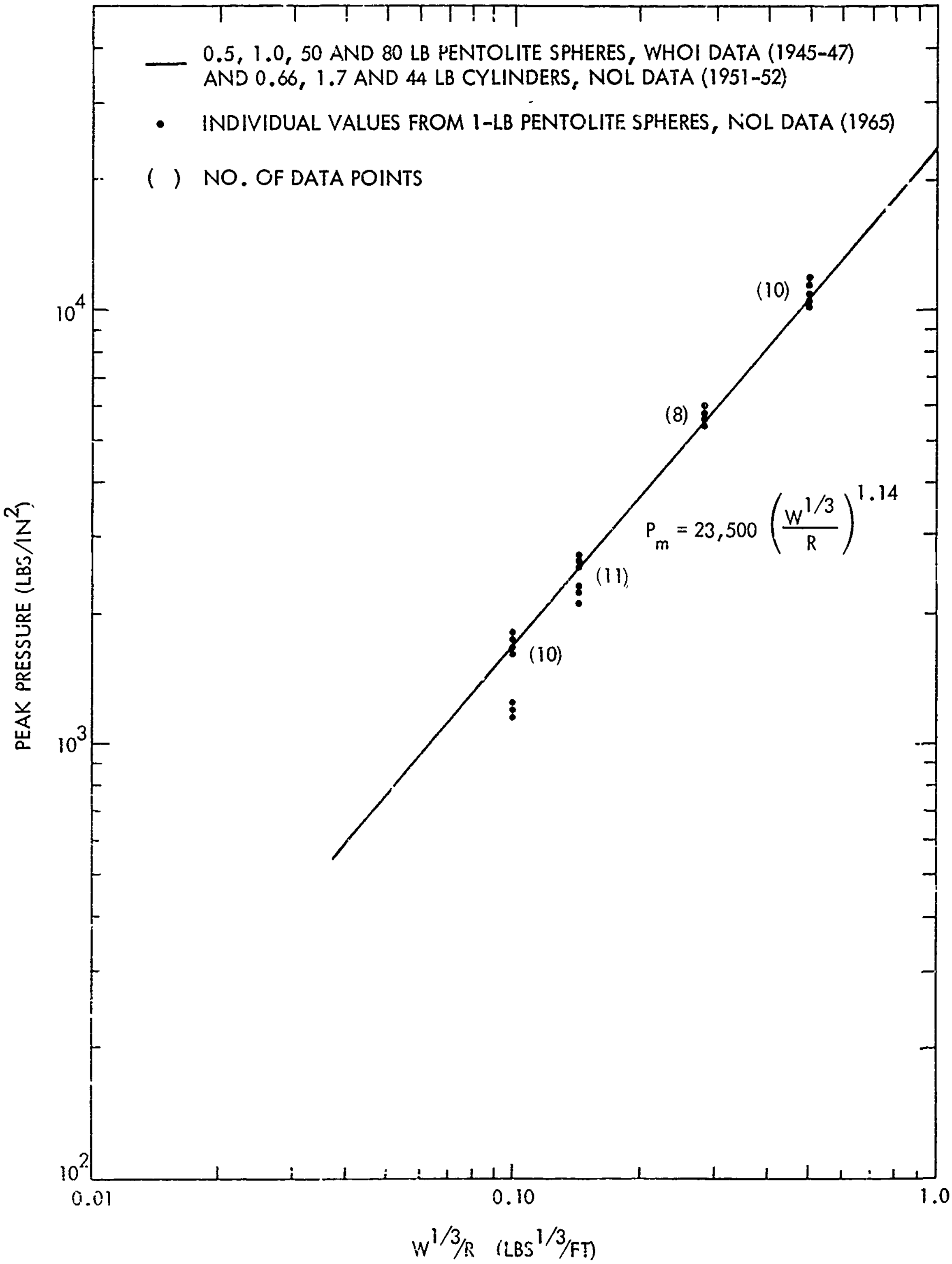

FIG.2 A COMPARISON OF RECENT WITH OLD U.S. MEASUREMENTS OF SHOCK WAVE PEAK PRESSURES FROM PENTOLITE (50/50)

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13 ABSTRACT

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